

Abstract.—Catch and effort data for the abalone *Haliotis rubra* fishery off Victoria, Australia, revealed that catches were allied to incentive (price); annual catch was proportional to effort. The robustness of the fishery can be attributed to low fishing mortality (F around 0.1) and a relatively high minimum length of capture (120 mm). Exploitation models showed that egg production was at least 50% that of unfished stocks. The analyses also showed that egg production was sensitive to variation in the growth parameters; fast-growing populations were more vulnerable to recruitment overfishing than slow-growing populations. For slow-growing populations, yields could be considerably increased without endangering recruitment. It is suggested, from the available evidence, that overfishing has been overemphasized in the collapse of abalone fisheries.

Exploitation models and catch statistics of the Victorian fishery for abalone *Haliotis rubra*

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Recent and comprehensive descriptions of the state of the world's abalone (*Haliotis* spp.) fisheries include reviews of the abalone fisheries in California (Tegner 1989, Tegner et al. 1989 and 1992), British Columbia (Breen 1986, Sloan and Breen 1988), Australia (Prince and Shepherd 1992), Mexico (Guzman del Proo 1992) and Japan (Mottet 1978). A unifying theme of these reviews is that abalone fisheries are characterised by initial high productivity followed by irreversible decline. Australia has developed an abalone fishery only recently by world standards. In Victoria, the fishery for the abalone *Haliotis rubra* is productive, valuable, and apparently stable (McShane 1990). The government limits the number of operators in the fishery (71), the annual catch (1460 metric tons) since 1988, and minimum length of capture (120 mm).

A fundamental objective of fisheries science is to predict the production from a fishery under varying management strategies. A common approach is to consider the yield from an individual or year-class of individuals under different fishing conditions (Beverton and Holt 1957, Ricker 1975, Gulland 1988, Megrey and Weststad 1988). Such exploitation models treat populations as the sum total of their individual members; yield is expressed as yield-per-recruit because the absolute level of recruitment is rarely known. Yield-per-recruit models have been applied to several abalone fisheries including

those for *H. discus discus* (Ishibashi and Kojima 1979), *H. iris* (Sainsbury 1982a), *H. laevigata* (Sluczanowski 1984), *H. kamtschathkana* (Breen 1986, Sloan and Breen 1988), *H. rufescens* and *H. corrugata* (Tegner et al. 1989), and the Tasmanian fishery for *H. rubra* (Nash 1992).

Although yield-per-recruit models can provide information on appropriate harvest strategies to maximize yield, the results provide no indication of the sustainability of a particular harvest regime. Because of the historical tendency of abalone fisheries to collapse, increasing attention has been focused on management strategies which maintain egg production as well as yield (Sluczanowski 1984 and 1986, Breen 1986, Sloan and Breen 1988, Tegner et al. 1989, Nash 1992).

In the present paper, the productivity of the fishery for abalone *Haliotis rubra* off Victoria, Australia, is described. To investigate the effect of growth rate, the relative yields of weight and eggs for two hypothetical populations of *H. rubra*, fast- and slow-growing, are examined. Management implications of my results are discussed for *H. rubra* as well as for other abalone species generally.

Materials and methods

Fishery statistics

Data on annual catch, effort, and price (whole weight) for the Victorian abalone fishery were obtained from

fishermen's returns and unpublished information supplied by the Victorian Fisheries Division. Information on the history of the Victorian abalone fishery was extracted from unpublished records supplied by the Victorian Fisheries Division (Dep. Conserv. Environ., 240 Victoria Pde, Melbourne 3002; see also McShane 1990).

Yield-per-recruit

Generalised fisheries exploitation models such as yield-per-recruit rely heavily on several assumptions. For any "unit stock":

1 Growth rates do not vary with time or density of the exploitable stock. Thus growth can be modeled with one set of parameters, e.g., the von Bertalanffy growth equation (Ricker 1975). Departures from these assumptions are known for abalone (e.g., Newman 1968, Sloan and Breen 1988, Day and Fleming 1992). However, for stocks of *H. rubra* the assumptions are reasonable (McShane et al. 1988a).

2 The rate of natural mortality is known and does not vary with age, time or density of the stock. Natural mortality is an important parameter in yield-per-recruit models, yet it is often the most difficult to estimate accurately. Natural mortality of *H. rubra* is constant with age after the first year (Shepherd et al. 1982, McShane 1991, Shepherd and Breen 1992). Estimates of natural mortality are in Table 1.

3 Fishing (F) and natural (M) mortality are independent of each other. For abalone fisheries, fishing mortality cannot be considered applicable to the entire fishery. Individual exploitation rates are applied to substocks opportunistically according to weather and incentive (Sluczanowski 1984, McShane and Smith 1989a). Incidental mortality can be caused by fishing, for example, wounding of undersize individuals (Sloan and Breen 1988, Tegner 1989, Shepherd and Breen 1992).

4 Recruitment is constant. Recruitment measured as the density of post-settlement individuals is highly variable for *H. rubra* (McShane et al. 1988b, McShane and Smith 1991). However, variation in growth rates of prerecruit individuals within a population acts to smooth out year-to-year variation in those *H. rubra* reaching harvestable size (McShane 1991).

5 Individuals of the same age have the same weight and susceptibility to capture. Individual variation in the relationships of weight to length and length to age has been demonstrated for *H. rubra*, but reasonable

Table 1

Estimates of rates of natural mortality (M) for *Haliotis rubra*.

Reference	Location	M(yr ⁻¹)
Beinssen and Powell (1979)	northeast Victoria	0.20
Nash (1992)	northern Tasmania	0.24–0.29
Shepherd et al. (1982)	South Australia	0.21–0.36
Prince et al. (1988)	southeast Tasmania	0.1–0.7

generalizations of these relationships can be made for the stock (McShane et al. 1988a, McShane and Smith 1992).

To investigate the effects of various rates of fishing, the yield-per-recruit equation of Ricker (1975:237) was used. The increase in length with age of *H. rubra* was computed using the von Bertalanffy growth equation

$$L_t = L_\infty(1 - e^{-K(t-t_0)})$$

where L_t is the shell length in mm of *H. rubra* at age t years, L_∞ is the hypothetical maximum length, K is the Brody growth constant, and t_0 is the hypothetical age when length is zero.

In calculating the yield-per-recruit of *H. rubra* at various ages, I assumed that individuals were recruited in the year corresponding to the minimum length at capture. The biomass of an individual of age t years, W_t (g), was assumed to be $0.00016 L_t^3$, where L_t is in mm (McShane et al. 1988a).

Egg-per-recruit

A simple age-structured model was used in which the relative abundance of females of age t years (N_t) was computed as

$$N_t = N_0 e^{-Zt}$$

where Z is total mortality ($F + M$). The egg production of a female of age t years (E_t) has a linear relationship with length (L_t) for *H. rubra* (McShane et al. 1988b) such that

$$E_t = 0.03 L_t - 2.4$$

where E is fecundity in millions of eggs, and L is shell length in mm; L_t is derived from the von Bertalanffy growth equation.

Total egg production (E_{tot}) is given by

$$E_{tot} = \sum_{t=0}^{t=25} N_t \cdot E_t$$

where $t = 25$ years is assumed to be the maximum age

Table 2

Parameters used in computations of yield and egg-per-recruit. Values for slow- and fast-growing populations of *Haliotis rubra* are derived from mark-recapture studies in Victoria, Australia (McShane 1990). Estimates provided are the von Bertalanffy growth parameters (see text for details).

Parameter	Fast	Slow
L_{∞}	152.1	139.7
K	0.37	0.20
t_0	-0.01	-0.12

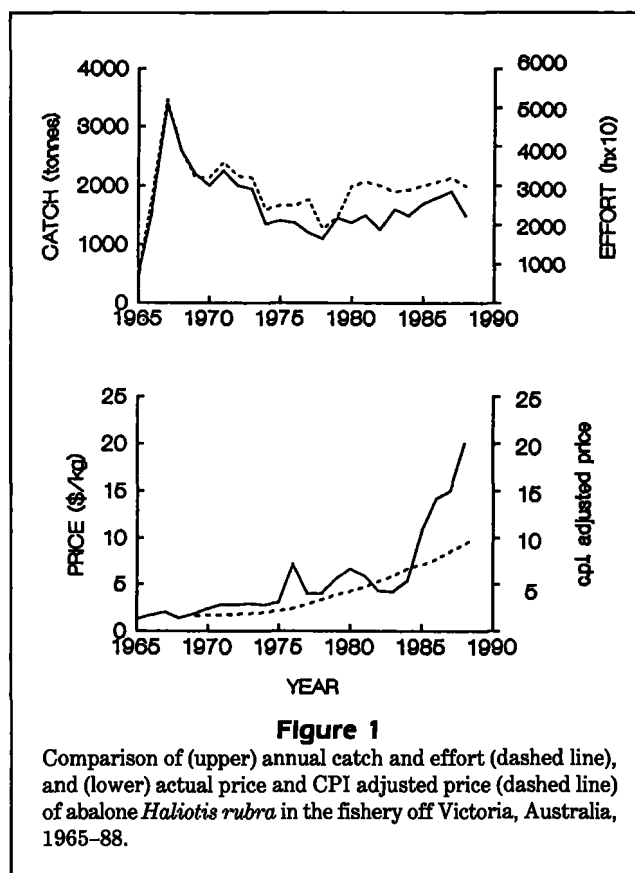
(McShane et al. 1988a). Egg production under various combinations of F , M , and minimum length-at-capture was compared with egg production of an unfished population ($F = 0$).

Fast- and slow-growing populations of *H. rubra* were modeled. The generalised growth parameters (Table 2) were based on empirical estimates (McShane et al. 1988a, McShane 1990, McShane and Smith 1992). Both yield and egg-per-recruit were expressed graphically as a function of minimum length-at-capture (i.e., length-at-recruitment) and F , using two rates of natural mortality estimated for *H. rubra* ($M = 0.1$ and 0.2 , Table 1). Length-at-recruitment was varied (in 10 mm increments) from 100 mm to 140 mm for fast-growing populations and from 70 mm to 130 mm for slow-growing populations. The value of F was varied from 0.1 to 1.5. A smooth surface was interpolated through points in 3-dimensional plots of yield and egg-per-recruit, following the method of McLain (1974) in which negative exponential weights are computed from distances between points in a regular grid and the irregularly spaced data points in the X-Y plane (Wilkinson 1990).

Results

Fishery statistics

Annual variations in catch, effort, and value of the Victorian abalone fishery are described in Figure 1. Catch is highly correlated with effort ($r = 0.98$, $n = 25$, $P < 0.001$). Although the catch rose in 1965–66 (accompanying development of export markets), the trend in both catch and effort is one of a slight but unalarming decrease followed by a slight increase during the 1980s. The introduction of catch quotas in 1988 is reflected in the decrease in catch in that year (Fig. 1). It is noteworthy that prior to 1988, price of abalone is a significant factor influencing the catch of the Victorian abalone fishery. Allowing for inflationary increases, the price of abalone doubled between 1967 and 1976–77 accompanying development of Japanese markets. Four

**Figure 1**

Comparison of (upper) annual catch and effort (dashed line), and (lower) actual price and CPI adjusted price (dashed line) of abalone *Haliotis rubra* in the fishery off Victoria, Australia, 1965–88.

exceptions to the steady rise in price have occurred. In 1967–68, a slight fall in price resulted from shipments of poor-quality abalone. Processing techniques were, at the time, in a developmental phase. Second, in 1976 an increase in price occurred concomitant with high demand by export markets and increased competition between processors for supply. The introduction of a competitive product, the Chilean “loco” *Concholepas concholepas*, on Asian markets coupled with buyer resistance to elevated prices of Australian abalone resulted in a decrease in price during 1977 (Stanistreet 1978). Note that there is a lag between price variation and catch and effort; the relative decrease in catch and effort in 1978 reflects the price drop in 1977 (Fig. 1). Buyer resistance also affected the price of abalone in 1981–82 and led to a decrease in effort and catch during this period.

More recently, the collapse of the large Mexican abalone fishery and the imposition of catch quotas on the Tasmanian and South Australian abalone fisheries (Prince and Shepherd 1992) decreased the world supply of abalone and increased the competitiveness of Victorian suppliers (McShane 1990). This and a decrease in the relative value of the Australian currency against

that of export markets resulted in a rapid increase in price of abalone during the 1980s.

Exploitation models

The yield and egg-production-per-recruit for individuals of various lengths under various levels of exploitation are shown for fast-growing (Fig. 2) and slow-growing (Fig. 3) populations of *H. rubra*. It can be seen that the relative yield-per-recruit is greater for fast-growing compared with slow-growing populations of *H. rubra*. The minimum lengths producing maximum yield-per-recruit are 130 mm for fast-growing populations and 120 mm for slow-growing populations. These maxima occurred at high exploitation rates ($F \sim 1$) and were independent of the natural mortality rates applied to the model (0.1, 0.2). Natural mortality had an obvious effect on the decline of yield-per-recruit with minimum length. For $M=0.2$, yield-per-recruit was less sensitive to variation in minimum length compared with $M=0.1$. Note that at realistic levels of F (0.1, McShane and Smith 1989a), yield-per-recruit is comparatively low (Figs. 2 and 3). For such low rates of exploitation, the model shows that for fast-growing (in contrast to slow-growing) populations, yield-per-recruit is relatively insensitive to variation in the minimum length-at-capture. Similar results were obtained from yield-per-recruit analyses of other species of abalone, provided that rates of fishing mortality are relatively low ($F < 0.3$) (Ishibashi and Kojima 1979, Sainsbury 1982a, Sluczanowski 1984, Breen 1986, Sloan and Breen 1988, Tegner et al. 1989, Nash 1992).

For fast-growing populations, exploitation rates producing maximum yield-per-recruit are associated with minimum egg production. Indeed, values of $F > 0.3$ are associated with egg production of less than 50% of an unfished population. Low egg production may cause recruitment failure in abalone stocks (Sloan and Breen 1988, Tegner et al. 1989). Egg production increases with minimum length; results of other studies show

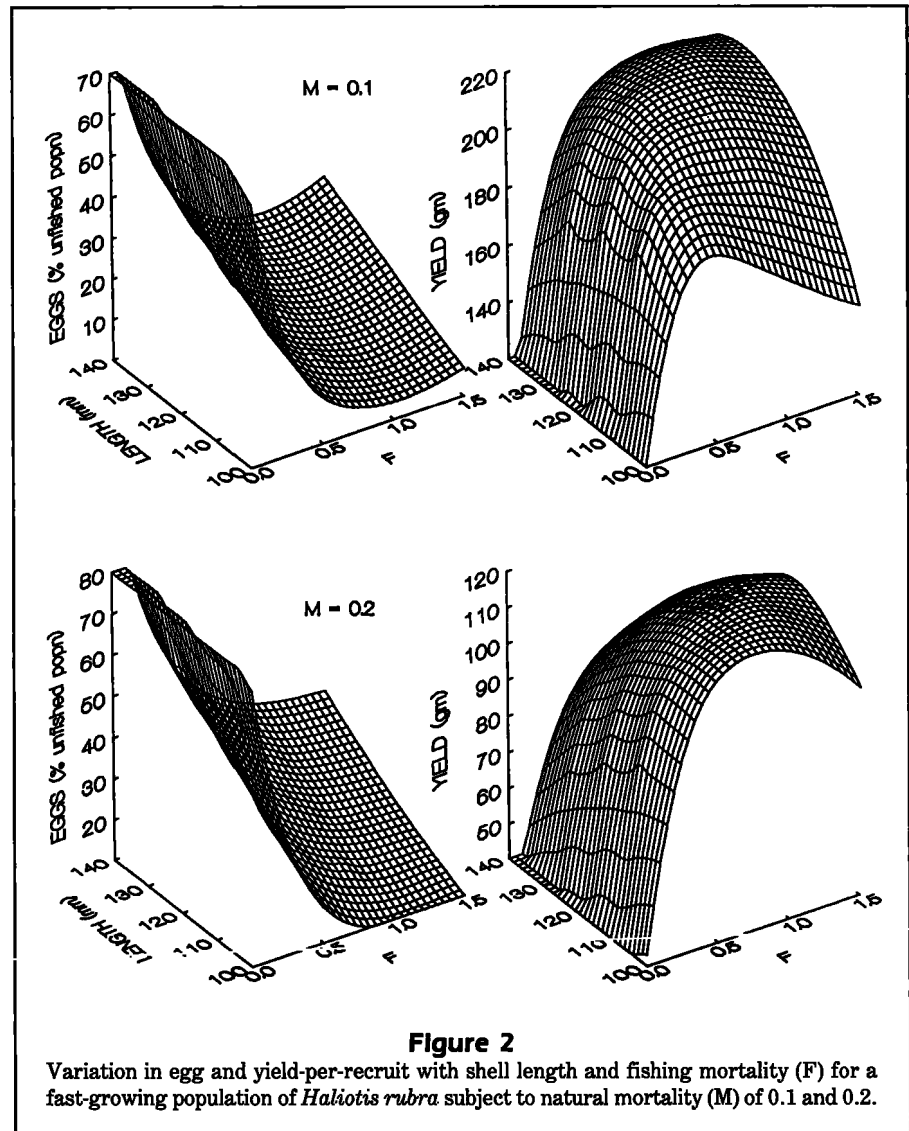


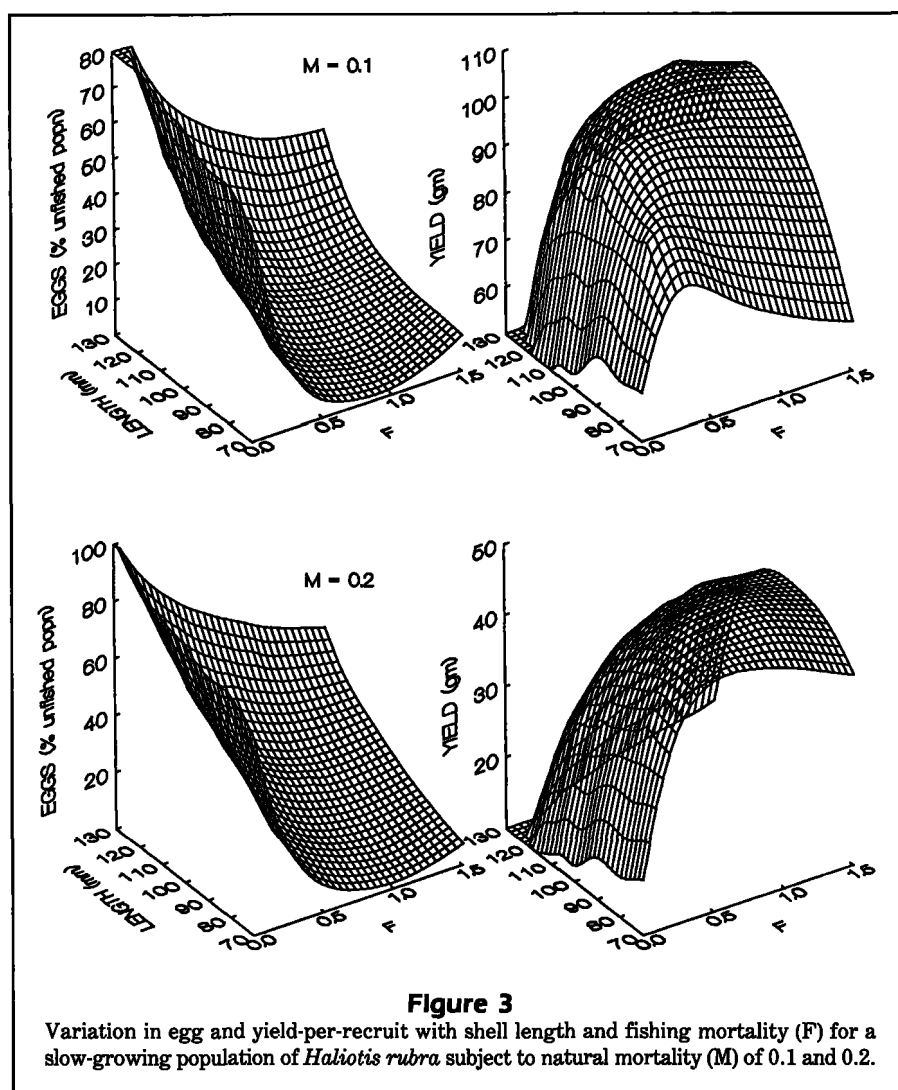
Figure 2
Variation in egg and yield-per-recruit with shell length and fishing mortality (F) for a fast-growing population of *Haliotis rubra* subject to natural mortality (M) of 0.1 and 0.2.

that fecundity of *H. rubra* is directly related to length (McShane et al. 1988b, Prince et al. 1988).

Egg production is less sensitive to variation in fishing mortality in slow-growing than in fast-growing populations of *H. rubra*. For minimum lengths over 120 mm, egg production rates are over 50% of an unfished population. At $F=0.1$, egg production is over 60% of that of an unfished population for both $M=0.1$ and 0.2.

Discussion

Catch levels for the Victorian abalone fishery suggest a robust fishery. But catch data are poor indicators of the stock abundance of abalone because fishermen can maintain catch rates by exploiting substocks (Breen



1980, Sloan and Breen 1988, McShane and Smith 1989a). Yet the available evidence is that the fishery is underexploited (McShane and Smith 1989ab; McShane 1990). Catches of *H. rubra* can be adjusted opportunistically by increasing effort when incentive (price) is high. Although Victorian abalone fishermen have the capacity to serially deplete substocks, rates of exploitation of *H. rubra* are generally low (see McShane and Smith 1989a). A surplus of harvestable individuals is maintained in substocks by the conservative fishing practices employed by Victorian abalone fishermen (McShane and Smith 1989a). With low exploitation rates ($F < 0.3$), the egg-per-recruit model shows that there is adequate egg production by individuals above the present legal minimum length of 120 mm. However, as a consequence of reaching harvestable size in about 4 years, prerecruit individuals from fast-growing populations have fewer years of egg

production than those *H. rubra* from slow-growing populations which reach harvestable size in about 10 years. Fast-growing populations of *H. rubra* are therefore vulnerable to recruitment overfishing should exploitation rates increase ($F > 0.3$). This is unlikely in the Victorian abalone fishery because both the number of operators and the annual catch are controlled.

Most abalone fisheries are generally subject to pulse fishing. Substocks are fished, then left to recover (Sluczanowski 1984, McShane and Smith 1989a). Fast-growing populations are important in this regard because they can be fished at a higher frequency than slow-growing populations (Sluczanowski 1984). Thus fast-growing populations are subject to higher exploitation rates than slow-growing populations. Slow-growing populations are often characterised by large accumulations of prerecruit abalone which are food-limited (Sloan and Breen 1988, McShane 1990). Egg-per-recruit analysis shows that even at extraordinarily high rates of fishing mortality ($F > 1$) egg production in slow-growing populations of *H. rubra* is above the assumed "safe" level of 50% of an unfished population

(Sloan and Breen 1988, Tegner et al. 1989). The model shows that slow-growing populations could be "fished down" at a reduced size limit and high exploitation rate without endangering egg production. Such a harvesting strategy could reduce the abundance of the accumulated stock to a level where food is no longer a limiting factor (McShane and Smith 1989b). To date in Victoria, such slow-growing stocks are rarely fished because of a paucity of abalone of harvestable size (McShane and Smith 1989b).

Why is the Victorian fishery for *H. rubra* apparently robust in contrast to other abalone fisheries? The viability of the Victorian fishery can be attributed to a relatively low number of operators (limited entry has operated in Victoria since 1968) and an associated low exploitation rate (see McShane and Smith 1989a). A minimum length that maintains a safe level of egg production provides further safeguards against recruit-

ment overfishing, as does an annual catch quota. However, size limits introduced to the California abalone fishery were also conservative but failed to arrest the decline of the fishery (Tegner 1989, Tegner et al. 1992). The combination of high commercial effort and intense recreational and illegal harvest resulted in a removal of surplus stocks in the California (Tegner et al. 1992) and Mexican (Guzman del Proo 1992) abalone fisheries. Unrestrained recreational and illegal harvest remains a threat to the Victorian fishery, but with a comparatively low human population and a relatively inaccessible coastline the Victorian abalone fishery is less vulnerable to noncommercial overfishing than the California or Mexican abalone fisheries (McShane 1990).

While fishing can deplete stocks, there are a multitude of other factors that affect the abundance of abalone. For example, overfishing could not explain the recruitment failure which occurred in the abalone fishery of British Columbia (Breen 1986, Sloan and Breen 1988). Recruitment failure in various species of abalone has been attributed to sea temperature anomalies (Hayashi 1980, Forster et al. 1982, Shepherd et al. 1985) or natural variation (Sainsbury 1982b; see also McShane and Smith 1991). The collapse of the California abalone fishery for *H. rufescens* coincided with predator release (Lowry and Pearse 1973, Hines and Pearse 1982, Tegner 1989, Tegner et al. 1989, 1992). The importance of predation in controlling abalone abundance is further exemplified by the recovery of stocks of *H. cracherodii* concomitant with a reduction in the abundance of major predators (Davis et al. 1992). The decrease in abundance of some California populations of abalone (*H. rufescens*, *H. cracherodii*) was attributed to low food availability caused by El Niño events (Tegner and Dayton 1987, Tegner et al. 1989), competition with other herbivores, and kelp harvest (Davis et al. 1992). Starvation in abalone causes a decrease in reproductive effort (Cox 1962) and an increased susceptibility to disease, both of which can cause a severe decline in stocks (Haaker et al. 1992, Tissot 1992). A major factor in the reduced abundance of abalone stocks in Japan is nearshore pollution (I. Hayashi, Igarashi-Jutaku 2-205, Niigata, Japan, pers. commun. 1990), a factor also implicated in the decline of California abalone stocks (see Tegner et al. 1992).

Variation in abiotic factors such as temperature have demonstrable effects on the survival and growth of exploited species (Cushing 1988). Such factors, apart from seasonal variation, vary stochastically and introduce uncertainty in fisheries management (Megrey and Weststad 1988, Walters and Collie 1988). Faced with this uncertainty, fishery managers must proceed cautiously and gain a better understanding of the

ecology of exploitable species, particularly of abalone which have a history of unexplained stock collapse.

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